TIME SERIES AND GEOSPATIAL DATA INTEGRATION FOR RESERVOIR SEDIMENTATION STUDY THAT INCORPORATES MULTIPLE SEDIMENTATION MODELS AND RATES FOR CONVERGENT VALIDATION

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Abstract: As part of the Tibble Fork Dam Rehabilitation Environmental Assessment, a sedimentation study was undertaken to determine the current and future storage needed to provide at least 50 to 100 years of dam life. Tibble Fork Reservoir, located in American Fork Canyon in Utah County, Utah, is a small, 259 acre-foot reservoir fed by a 35 square-mile watershed, with an average elevation of 8,600 feet above mean sea level. Multiple analyses were used to determine erosion rates from the Van Dugway landslide and watershed sediment yields that directly contribute sediment into Tibble Fork Reservoir. Tibble Fork Reservoir was constructed with assistance from the U.S. Department of Agriculture, Soil Conservation Service, now the Natural Resources Conservation Service (NRCS), in 1966. Construction of the dam was accomplished through the authority of the Watershed Protection and Flood Protection Act, Public Law 566 (PL-566). NRCS is developing a dam rehabilitation plan for the dam that includes an auxiliary spillway analysis, sedimentation volume calculations, and seismic/geotechnical analyses to meet current dam safety criteria.

In 2012, Todea and Hasenyager made a sedimentation study of the Tibble Fork (Todea and Hasenyager, 2012). The results of that study were compared to new calculations as part of the dam rehabilitation environmental assessment study. Bedload measurements were taken during the 2011 spring runoff and were modeled using the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Centers River Analysis System (HEC-RAS) sediment transport model to estimate the sediment contribution (USACE, 2010). The RiverMorph and FlowSed/PowerSed (RIVERMorph, 2008) models were used to determine annual average bedload and suspended sediment loads from the 2011 spring runoff event. The Automated Geospatial Watershed Assessment (AGWA) (Burns et al., 2007) software, and the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1994) were evaluated to estimate the watershed sedimentation rates that contribute to the reservoir. As part of the 2012 study, the Bridges 1973 sedimentation map was reviewed and correlated to the above studies. The following models resources were also considered:

1) The "*Managing Sediment in Utah's Reservoirs*" Utah State Water Plan produced by the Utah Division of Water Resources (UDWR) in 2010. Four reservoir sedimentation rates were filtered and compared due to the elevation and location of the reservoirs.
2) The Rangeland Hydrology Erosion Model (RHEM) (Nearing et al., 2011) is a slope-based program, not applicable for high alpine watershed erosion scenarios, but the model was used as part of this study.
3) Slaymaker (1977) reported on eleven relevant basins in the report "*Estimation of sediment yield in temperate alpine environments*."

Trap efficiency of the reservoir was considered and calculated using the USDA SCS (1975, revised) procedure titled "*Procedure-Sediment Storage Requirements for Reservoirs – Technical Release No. 12*" (TR 12).Finally, all methods were compared to bathymetric surveys that were conducted in 2010 and 2014.

The results of the 2012 study by Todea and Hasenyager estimated that an average 2.62 acre-

feet per year of material is deposited in Tibble Fork Reservoir. The compilation of sediment rates from the nine evaluations in the 2012 study ranged from 0.02 to 0.76 acre-feet per square mile, with most values ranging near or below 0.10 acre-feet per square mile. The 2014 bathymetric survey estimated an average annual sedimentation rate of 2.92 acre-feet (or 0.08 acre-feet/square mile) in the pool. This assumes that the original pool was accurately measured at 259 acre-feet of storage for the original design. The 1964 design sediment rate was calculated to be 3.32 acre-feet per year on average, this includes considering trap efficiency. Bridge's 1973 map is a good tool for providing initial estimates. Pairing of results from Rivermorph PowerSed/FlowSed with bedload and suspended sediment, HEC-RAS bedload with RiverMorph PowerSed/FlowSed suspended sediment, and AGWA SWAT with HEC-RAS bedload provided useful results. The RHEM is not optimally suited for these environmental conditions, but provides supporting documentation. Trap efficiencies in TR 12 (USDA SCS, 1975) are relevant.

INTRODUCTION

This study is a continuation of a sedimentation study performed by Todea and Hasenyager in 2012 for the Tibble Fork Reservoir. Todea and Hasenyager (2012) contains the following introduction: *"As part of a dam rehabilitation plan for a constructed Watershed Protection and Flood Prevention Public Law 566 (PL-566) dam, a sedimentation study was undertaken for Tibble Fork dam. Tibble Fork Reservoir, constructed in 1966, is located in American Fork Canyon in the Wasatch Mountains of Utah (Figure 1). To meet United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) Watershed Rehabilitation Program objectives, the dam rehabilitation outcome must have a design life of no less than 50 years* [and no more than 100 years]. *As part of the rehabilitation plan, alternatives that include decommissioning of the dam were analyzed. Sedimentation accrual within a dam and the effects on the design life must be considered when a dam is being rehabilitated. The original project in 1966 estimated a sediment storage capacity of 3.32 acre-feet/year (USDA SCS, 1964). The Van Dugway landslide located approximately 6,400 feet upstream has been actively contributing additional sediment to the reservoir since 1966. Multiple analyses were conducted to determine bedload gradation and suspended sediment material that is being deposited in Tibble Fork Reservoir*".

The components of the Todea and Hasenyager 2012 study were compared to a 2014 bathymetric survey. As part of this study the following were reviewed, modeled, or calculated:

- The Utah State Water Plan – "*Managing Sediment in Utah Reservoirs*" was reviewed and four dams that meet comparative requirements were reviewed.
- The Rangeland Hydrology Erosion Model (RHEM (Nearing et al., 2011) was calculated for a hillslope.
- Measured data from Slaymaker (1977), a sediment yield in temperate alpine environments study, were used.The Bridges 1973 sedimentation map was reviewed and sediment yield was determined for the Tibble Fork watershed study area.
- Trap efficiency (USDA SCS, 1975) was calculated and applied to the comparative sedimentation analysis.

The Todea and Hasenyager 2012 study used sedimentation techniques that include components from AGWA SWAT (Burn et al., 2007, and Arnold et al., 1994); bedload and sediment transport models from HEC-RAS; and Rivermorph FlowSed/PowerSed models

with bedload from the 2011 spring runoff measured upstream of the reservoir.

Figure 1 Tibble Fork Watershed Location Map (Todea and Hasenyager, 2012)

BACKGROUND

The Tibble Fork watershed is 35 square miles in area, at an elevation of 8,600 feet above mean sea level. The Van Dugway Landslide has contributed large amounts of sediment to the American Fork River for a reach length of 1,500 feet. The actively eroding portion of the landslide is located on the north, or right bank (looking downstream) of the American Fork River. The highest section of the landslide on the right bank of American Fork River is approximately 50 feet tall (Figure 2).

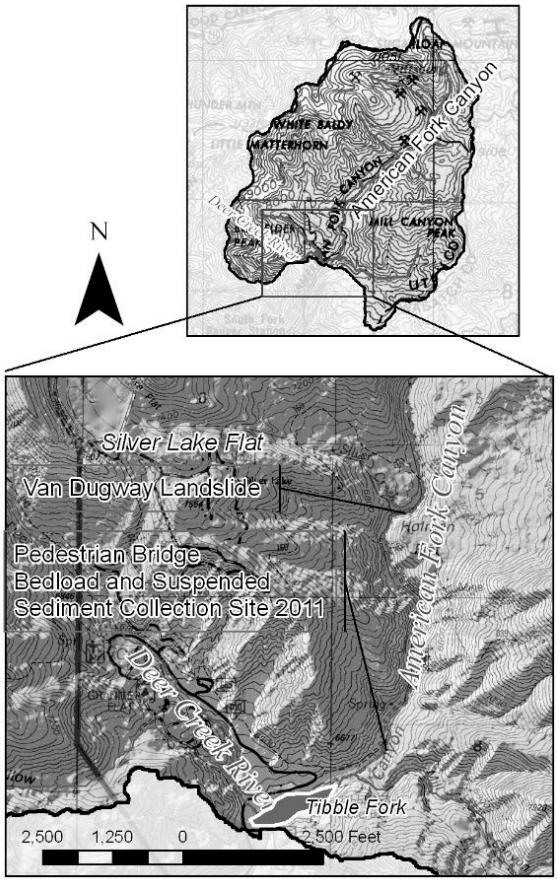

Figure 2 Tibble Fork Reference Map (Todea and Hasenyager, 2012)

The American Fork Canyon has a drainage area of approximately 26 square miles, and the adjacent Deer Creek has a 9.5-square-mile drainage area. They interconnect at the Tibble Fork Reservoir, providing a total watershed contribution area of 35.5 square miles (Figure 2). The American Fork Canyon drainage area contains the Van Dugway landslide. Below Van Dugway landslide, the American Fork River is characterized as a steep, confined valley with a Rosgen channel type B (Rosgen, 2006), that provides transport of large bedload material. Bedload samples were collected as part of Todea and Hasenyager (2012) study at a pedestrian bridge that crosses the river 2,700 feet upstream of Tibble Fork Reservoir, where the valley opens slightly and the channel is a Rosgen type C, which allows for transport of large cobbles at larger flows. Downstream from the pedestrian bridge to the Tibble Fork Reservoir the channel is a braided, Rosgen type D, where cobbles and gravels are deposited. The braided channel has distinct deposits of bed materials where the upper portion contains cobbles and the lower portion contains sand and fine gravels. Light Detection and Ranging (LiDAR) data were collected by Aero-Metric, Inc. (2010) as part of the Todea and Hasenyager (2012) study and was used for the hydraulic analysis.

Bathymetric data was collected by AMEC under contract with the NRCS in 2010 (AMEC, 2010). The bathymetric data and NRCS as-built drawings at ten-foot contours were analyzed by the Utah Division of Water Resources in 2011 to determine the volume of sediment contributed to the Tibble Fork Reservoir. It was determined that the sediment contributed to Tibble Fork Reservoir was between 84 and 142 acre-feet from 1966 to 2010 (UDWR, 2011), at an average rate of 1.91 to 3.23 acre-feet/year. This is approximately 1.41 to 0.09 acre-feet/year lower than the original estimate of 3.32 acre-feet/year. HDR Engineering, Inc. (2011) provided a study that resulted in a sedimentation rate of 2.21-2.82 acre-feet/year.

During the 2011 spring runoff, bedload and suspended sediment was measured. The Elwha bedload sampler was used to collect bedload material. A total of four samples was collected that included the rising and falling limb of the hydrograph of the spring runoff. Both the bedload and suspended- sediment samples were collected using guidance from USGS Field Measurements for Measurement of Fluvial Sediment (Edwards and Glysson, 1999). Suspended sediment was collected using a US DH-48 sampler. It is noted in the 2012 Todea and Haseyanger study *"Although the bedload is at a lower rate on the falling limb than the rising limb, the suspended sediment has the largest concentration of material captured on the falling limb of the hydrograph"*. This could have had an effect on the results that is artificially increasing the bedload and decreasing the suspended sediment, if only the rising limb values were used, resulting in higher bedload and lower suspended sediment values.

The purpose of the 2012 Todea and Hasenyager 2012 study was to obtain a more accurate estimate of sedimentation rates and provide information to determine the validity of mitigating the Van Dugway landslide. In 2011, NRCS conducted a bedload and suspended-sediment sampling program during the spring runoff on the American Fork River, below the Van Dugway landslide and above Tibble Fork Reservoir at the pedestrian bridge.

The Todea and Hasenyager study used multiple software programs and computations from collected bedload and suspended sediment approximations to narrow the range of estimates of sediment transported to Tibble Fork Reservoir. The Automated Geospatial Watershed Assessment (AGWA) (Burns et al., 2007) that uses Soil and Water Assessment Tool (SWAT) (Arnold et al, 1994) was evaluated to estimate watershed sediment yields. The RiverMorph (2008) FlowSed/PowerSed model was used with measured bedload to estimate the annual average bedload that passes through the sampling site. The AGWA SWAT model for the American Fork River (using 26 square miles of contributing area) calculated that 2,196 tons of material, on annual average, is transported into Tibble Fork Reservoir.

The Todea and Hasenyager study also used the HEC-RAS sediment transport model to estimate bedload contributions from the Van Dugway landslide and American Fork Canyon, and to determine the amount and gradation of bedload material being deposited into Tibble Fork Reservoir. The bedload data was collected during the one-percent recurrence interval from the spring runoff of 2011. The bedload material collected during the spring runoff was modeled by HEC-RAS as an estimate, until it mimicked observed and measured bed material from below the pedestrian bridge to Tibble Fork Reservoir. Four 100-pebble counts of the bed material were conducted from the pedestrian bridge to Tibble Fork Reservoir and used in the HEC-RAS model. The Yang (1972) transport function, Exner 5 (USACE, 2010) sorting method, and Rubey (1933) fall velocity method were used for sediment transport functions within HEC-RAS. USGS stream gage 10164500 15-minute discharge data was reduced by ten percent and used in the HEC-RAS model. Finally, United States Geological Survey (USGS) gage peak flow data (USGS, 2011), and flow frequency bedload curves were used to estimate bedload transport to the reservoir in Microsoft Excel, and to analyze the gradation of the material deposited as estimated from the HEC-RAS sediment transport model. The HEC-RAS sediment transport model calculated that of the 5,086 tons of material that passed below the pedestrian bridge in 2011, only 2,059 tons were actually deposited in the Tibble Fork Reservoir. The material that was deposited in Tibble Fork included fine gravel, very-fine gravel, and coarse sand.

Todea and Hasenyager (2012) used RiverMorph FlowSed/PowerSed to estimate annual

average bedload using a defined period within the stream gage records. Bedload measurements and estimated suspended sediment from the 2011 survey were used to calculate user-defined bedload and suspended sediment curves to be input into the RiverMorph model. Flow durations curves were generated in RiverMorph using records from the USGS stream gage 10164500 (USGS, 2011). RiverMorph FlowSed/PowerSed model and user-defined bedload and suspended sediment curves estimate an annual average bedload transport rate of 3,624 tons/year and a suspended sediment rate of 5,748 tons/year that passes under the pedestrian bridge at the collection site.

METHODS

The 2012 Todea and Hasenyager study (i.e. the 2010 bathymetry; bedload study from the Van Dugway landslide; HEC-RAS sediment transport model to Tibble Fork Reservoir; the RiverMorph FlowSed/PowerSed model calculations of material moving through the system annually) were compared to the 1973 USDA sedimentation maps, selected dams in the Utah Divisions of Water Resources (UDWR) sediment study for reservoirs, the study on sediment yield in temperate alpine environments (Slaymaker, 1977), and the Rangeland Hydrology Erosion Model (Nearing et al., 2011). USDA SCS Technical Release TR 12 "*Procedure--Sediment Storage Requirements for Reservoirs* was also evaluated and applied to all sediment rates to determine the range and applicability of sedimentation applications. Finally, 2014 bathymetry measurements were taken with a Z-Boat to determine current volumes or capacity of the reservoir.

The Bridges 1973 map entitled "*Estimated Sediment Yield Rates for the State of Utah*" has many referenced data sources as part of the map, including:

- Great Basin Upper Colorado and Lower Colorado Regions, Comprehensive Framework Study, Appendices VIII, Water Management, June 1971, Pacific Southwest Inter-Agency Committee/Water Resources Council,
- Utah State soils map and soil descriptions,
- Reservoir surveys by NRCS and USBR,
- Suspended load measurements by USGS, USGR and NRCS,
- Watershed studies by SCS/NRCS, and
- General knowledge of the state from regular NRCS program work.

Bridges notes "*Do not use these rates to determine sediment yields at specific sites. Large variations in sediment rates may occur within the delineated areas*".

The 2010 UDWR sediment study for the reservoir provides reference to 18 Utah dams, and includes tables provided by the nationwide REServoir SEDimentation Database (RESSED). As stated by UDWR, *"Sedimentation data exist for only 18 of Utah's major reservoirs; that is, those larger than 1,000 acre-feet. Much of these data comes from reservoir surveys conducted between 1930 and 1975 by the U.S. Soil Conservation Service (now the Natural Resources Conservation Service, NRCS) and the U.S. Bureau of Reclamation. The data were collected and published in a national summary of reservoir sediment deposition surveys (Dendy and Champion, 1978). This nationwide database was revised in 2009 and is now the REServoir SEDimentation Database (RESSED) available online at http://ida.water.usgs.gov/ressed/ and http://pubs.usgs.gov/ds/ds434/. The database is a cumulative historical archive that includes data from 1755 to 1993. The 1,823 reservoirs included in the database range in size from farm ponds to the largest U.S. reservoirs. Results from 6,617 bathymetric surveys are available in the database,*" (UDWR, 2010).

Table 1 illustrates data from four dams in the UDWR (2010) study used in the Tibble Fork project. The elevation of the reservoirs were also taken into consideration.

Table 1 Utah Department of Water Resources, reported sediment in selected reservoirs

Reservoir	Date Built	Storage Capacity Initial Survey (AF)	Drainage Area, square miles	Period Assessed	Sedimentation Rate (percent annual capacity loss)	Estimated Annual Sediment Volume (acre-	Average Annual Sediment Volume per mi^2 of DA	Estimated Capacity of Loss as of
Booby Hole	1895	607	5	1895-1940	0.03	0.2	0.024	3
Indian Creek #1	1898	318	12	1898-1940	0.14	0.45	0.038	16
Duck Fork	1942	718	3.4	1942-1962	0.07	0.5	0.14	5
Iliff Anrus	1949	20	1.1	1949-1966	4.1	0.82	0.76	100

The 1977 Slaymaker study, "*Estimation of sediment yield in temperate alpine environments*" was reviewed to compare measured sediment yield at specific sites. The purpose of the Slaymaker paper was to compare sediment yield data and measurements of geomorphic process. Out of five locations and eight river basins, the Rio Nambe in the Sangre de Cristo Mountains was selected as the most applicable comparative site, based on available data, elevation, and watershed size.

As described by the RHEM developers (Nearing et al., 2011), "*RHEM is an event-based derivation of the WEPP model made by removing relationships developed specifically for croplands and incorporating new equations derived from rangeland data. RHEM estimates runoff, erosion, and sediment delivery rates and volumes at the spatial scale of the hillslope and the temporal scale of a single rainfall event*". SSURGO data was used to characterize the types of surface texture of the soils to be entered into RHEM. Precipitation data were pulled from the RHEM list of available stations that best matched the upper American Fork watershed. The hillslope was considered uniform and represented only a few slopes. Shane Green, a Range Conservationist with the NRCS, was consulted on the foliar cover percent averages for the study area.

In addition to the methods described above, USDA SCS Technical Release TR 12 (1975), "*Procedure – Sediment Storage Requirements for Reservoirs*" was evaluated and compared to the Todea and Hasenyager (2012) results. This was done to provide a reference calculation for sediment yield to material deposited into the Tibble Fork Reservoir. TN 12 provides trap efficiencies of reservoirs using the watershed size, reservoir capacity, and runoff, which are calculated into a Capacity – Inflow ratio. A curve for trap efficiency of reservoirs is also used based on the capacity-inflow ratio. TN 12 contains three sediment curves that include: 1) bedload or coarse material (highly flocculated and coarse-grained sediments); 2) colloids, dispersed clays, and fine silts and; 3) sediment consisting of a wide distribution of various grain sizes. The curve associated with colloids, dispersed clays, and fine silts was used for this study.

A Z-boat was provided by the Wyoming NRCS State office, and the survey was completed in July, 2014. The Z-boat is a remotely-operated survey boat that uses both Global Positioning Systems and echo sounders to receive location and associated depths (OceanScience, 2014). The Z-boat data were correlated to LiDAR data that had been was gathered for this project. The combined data were used to define a continuous terrain and to determine current

sediment volumes within the reservoir.

RESULTS

The range of values derived from the above methods is 0.02 – 0.76 acre-feet per square mile. When considering trap efficiencies, the range is 0.67 – 21.28 acre-feet per year. Table 2 illustrates annual sediment rates calculated in associated tons, including reservoir trap efficiencies for final deposition into Tibble Fork Reservoir. Also included are the 2012 Todea and Hasenyager values with reservoir trap efficiencies.

Table 2 Sedimentation results based on sediment yield and deposited material into Tibble Fork Reservoir

Method/Location/ Study	tons/year	Area Sq. Mi.	Estimated Annual Sediment Volume (acre-feet)	Average Annual Sediment Volume per mi of DA (AF/mi^2/yr)	With 20% trap efficiency, final sediment value in Tibble Fork
Booby Hole (UDWR, 2010)		35**	0.84	0.02*	0.67
Indian Creek #1 (UDWR, 2010)		35**	1.33	0.04*	1.06
Duck Fork (UDWR, 2010)		35**	4.90	0.14*	***3.92***
Iliff Anrus (UDWR, 2010)		35**	26.60	0.76*	21.28
Yield Class 5, 0.1-0.2 Ac-ft/Sq.Mi./Yr (Bridges,1973)		18	3.60	0.20*	***2.88***
Yield Class 6, less than 0.1 Ac-ft/Sq.Mi./Yr (Bridges,1973)		17	1.70	0.10*	1.36
Yield Class 5 + 6 (Bridges, 1973) TOTAL		35	5.30	0.30*	***4.24***
Temperate Alpine -- Sangre de Cristo Mountains (Rio Nambe) – (Slaymaker, 1977)		35**	0.84	0.02*	0.67
AGWA SWAT (interpolated)	2928.0*	35	1.25	0.04	1.00
RiverMorph FlowSed/PowerSed (suspended)	5748.0*	35	2.46	0.07	1.97
RiverMorph FlowSed/PowerSed (bedload)	3624.0*	35	1.55	0.04	1.24
RiverMorph FlowSed/PowerSed (suspended+bedload) TOTAL	9372.0*	35	4.01	0.11	***3.21***
HEC RAS Sedimentation	1403.6*	35	0.60	0.02	0.48
RiverMorph FlowSed/PowerSed suspended + HEC-RAS Bedload TOTAL	7151.6*	35	3.06	0.09	***2.45***
RHEM	14995.2	35	6.41	0.18	5.13
Z-Boat bathymetry (2014)			3.65	0.08	***2.92*** *

*Denotes method and how the data were initially captured.
**Denotes that watershed is normalized and interpolated to have consistent units.

The UDWR reservoir study has the largest differences among its dataset. However, the Duck Fork Reservoir does fall within an acceptable range. Of the four dams reported in this study, this dam has the highest elevation above mean seal level. The Iliff Anrus Reservoir location is currently unknown. The mean elevation of the Duck Fork Reservoir is 9,300 feet above

mean sea level. The mean elevation of the Tibble Fork watershed is 8,600 feet. The elevation difference between the Duck Fork and Tibble Fork watersheds is significant enough for the UDWR reservoir study to provide a cursory approximation or provide ranges when conducting sedimentation studies.

Bridges' sediment map provided the best results with the easiest amount of effort. At first glance, this method appears to be a good verification tool. However, as suggested by Bridges (1973), this method should not be used to determine specific yields at specific sites.

Of the Slaymaker (1977) sites, the Rio Nambe in the San de Cristo Mountains provided the best- suited environmental setting range. However, it did not correlate well. Nor did the AGWA SWAT interpolated results. This is due to user unfamiliarity and the variation of values that could be applied within the software. The Rivermorph FlowSed/PowerSed (bedload and suspended sediment) did correlate well.

The known transported bedload to Tibble Fork was computed by HEC-RAS. The number could be nearly half of the 3,624 tons of material that moved through the measured site using RiverMorph FlowSed/PowerSed opposed to what was modeled in HEC-RAS. That is, the HEC-RAS model provides results of 1,403.6 tons that was computed to reach the Tibble Fork pool.

The RHEM numbers did correlate well and estimated high, since only one hillslope face was estimated for the entire watershed. Due to the limited data fields of the program, it is reasonable to believe that with more hillslope entries, the sediment yield may be more accurate. Note that RHEM is not applicable due the tolerance of hillslope lengths being exceeded.

The Z-boat calculations produced an annual sediment deposition rate of 2.92 acre-feet per year. With the trap efficiency of 20 percent, the sediment yield is expected to be 3.63 acre-feet per year.

CONCLUSION

Having actual measurements provided confidence in the modeled results. As previously mentioned, the Bridges map narrowed down values to get a realistic picture of the potential for sediment deposition. The Utah dams could be further analyzed to determine sediment yields and trap efficiencies. The author does not fully endorse the use of AGWA SWAT due to his limited use and knowledge of the software. The potential of using the software to accurately provide sediment yields may be promising.

Although a bathymetric survey was supplied, additional familiarity with sedimentation methods is required to predict future conditions. Data acquisition using historic flows, the stream gages, and SSURGO data are precursors to understanding the sedimentation within the system. As mentioned before, the Todea and Hasenyager bedload study provided insight that data on the rising limb of the hydrograph are the most critical, however, both the falling and rising limbs were considered in the sediment-discharge curves, and this artificially raised the amount of bedload being transported to Tibble Fork. Ideally, all possible sediment would be accounted for. Understanding the process of sedimentation is crucial for dam design, as it has an impact on dam size and the longevity of the structure. The system of averages may be too general, but using many methods may be validated due to the consequences of under- or over-estimating the sediment that is either being delivered or moved through the reservoir.

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